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From Process to System: A Review on the Implications of Concrete 3D Printing on Project Delivery †

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Abstract: The aim of the study is to question the need for alternative project delivery methods to foster the integration of concrete 3D printing in the construction industry. For this purpose, a literature review was carried out. The results indicate that the traditional planning and construction process will have to be reconsidered. On the one hand, new roles and changes in responsibilities may emerge, and, on the other hand, a holistic design process and an early contractor involvement will be required to fully exploit the potential of concrete 3D printing. Therefore, alternative project delivery models need to be adopted.

Keywords: Project Delivery; Concrete 3D Printing; Construction Industry

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1. Introduction

In the recent past, additive manufacturing has been the subject of a great deal of attention through university research and prototypical industrial application for the production of cement-based components as an alternative construction method to conventional formwork concrete construction [1]. While experimental application and proof of concept of concrete-based additive manufacturing processes have been taking place since the late 1990s and early 2000s, practical (industrial) application in the construction industry is still in its infancy [2].

Ongoing academic and industrial research focuses on different processes (extrusion, spraying, particle bed printing), materials (mortar, geopolymers, recycling concrete), implementation methods (in-situ, on-site or off-site) and application strategies (print-only or hybrid) as well as different use cases or functions ((non-)load-bearing; topology optimised or functionally integrated components) [3,4]. Currently, the extrusion process, based on the developments of Contour Crafting (CC) [5] and Concrete Printing (CP) [6], is the most promising type for a rapid integration into the (in-situ) construction process. In extrusion-based concrete additive manufacturing, a premixed material is freely deposited (and layered vertically) as very fine filament mostly with a diameter of 4-10 mm along a defined print path through a robot-guided nozzle [2]. With very fine filament strands, a sufficiently high print resolution can be achieved. Coarser filament strands, on the other hand, lead to a fast application rate.

1.1. Potential of Concrete 3D Printing (C3DP)

The use of concrete additive manufacturing methods not only opens up the possibility of using concrete in a way that conserves resources, but also leads to the elimination of formwork as far as possible through the direct construction of the structure. This not only offers the prospect of far-reaching improvements in productivity, but also enables the production of shape-optimised, non-standard components [7]. Selective and layered structural design also offers the possibility of integrating other functions (e.g. insulation or electrical installations) into the components.

1.2. Problem Statement and Research Gap

Due to the lack of practical reinforcement strategies and regulations, extrusion is often used (only) as an alternative to conventional masonry construction [8]. In the case of 3D-printed buildings to date, the application of C3DP is predominantly focused on the fabrication of walls and therefore only represents a comparatively small part of the overall context of a construction project with regard to required ceilings, structural connections, windows and doors or electrical, sanitary or air-conditioning systems. For concrete 3D printing, however, to benefit from the automated fabrication, possible interface problems resulting from subsequent (manual) fabrication and assembly processes need also to be taken into account at an early stage in the 3D-Printing design process. This might lead to implications of concrete 3D printing on project delivery that have hardly been investigated so far with regard to project organisation, responsibilities or decision points.

1.3. Aim and Scope of this Paper

Despite numerous pilot buildings, C3DP is still a niche technology, and its implications on project delivery in terms of project organisation, responsibilities or decision points has not been widely researched. In the aforementioned context, the question arises as to what extent concrete 3D printing can be integrated with the current structures of the planning and construction process and what is necessary to further foster this integration. The aim of this study is to provide an overview of the existing literature about the implications of concrete 3D printing on traditional project delivery and to question the need for alternative project delivery models. For this purpose, a literature review was carried out in order to record the previous findings on the implications of C3DP on project delivery.

2. Method

To address this topic, initial keywords were chosen in a first step to gather relevant papers from research, industry, and conference perspectives. The timeframe of the last ten years was selected using ScienceDirect. The keywords used were "3D print*," combined with "project delivery", "organizational structures" or “project organisation”, and "construction”, “construction process”, “construction supply chain” or “construction industry”.

Our search provided only limited results, even though alternative literature has addressed similar research questions. A total of only 6 papers were collected, with one duplicate and 1 paper being considered relevant to the topic. This is a strong indication that the implications induced by C3DP on project delivery may not have received a significant amount of attention in the academic literature. This phenomenon is not uncommon, as emerging fields like C3DP may not yet have been investigated on all levels in full detail and somehow still missing in databases. Research on C3DP is mostly still focused on material-process-interaction, rather than on management aspects.

To ensure a comprehensive understanding, the search was complemented by looking beyond these databases. This approach allowed a holistic exploration, even when traditional databases did not provide direct results. As a result, the following literature was considered as original work and therefore of upmost relevance:

Table 1. Original Work in the light of implications of C3DP on Project Delivery.

Year	Source	Author	Title
2016	[9]	Kothman / Faber	How 3D printing technology changes the rules of the game

2018	[10]	De Schutter et. al.	Vision of 3D printing with concrete — Technical, economic and environmental potentials
2018	[11]	Garíca de Soto et. al.	Rethinking the roles in the AEC industry to accommodate digital fabrication
2019	[12]	Garíca de Soto et. al.	Implications of Construction 4.0 to the workforce and organizational structures
2020	[13]	Ghaffar / Corker / Mullet	The potential for additive manufacturing to transform the construction industry
2023	[14]	Ayyagari / Chen / García de Soto	Quantifying the impact of concrete 3D printing on the construction supply chain
2023	[15]	Spicek / Radujkovic / Skibniewski	Construction project organisation for 3D printing technology

3. Results and Discussion

Based on the existing and complemented literature, four major implications can be derived, that are elaborated in detail below: (1) Forward shifting of decisions to early design stages, (2) Integration of construction expertise into the design stages, (3) Changes in traditional roles and evolution of new roles, and (4) transformation of organisational structures.

3.1. Forward shifting of Decisions to early design stages

In C3DP, the digital model is directly translated into a physical component through robotic manufacturing. In particular, the necessary boundary conditions of different printing strategies (in-situ or full-building print) and methods, but also the possibilities of different printing parameters such as filament size and width, as well as material-technological dependencies such as printing time, can vary greatly. Therefore, they must be integrated into the design process at an early stage [15–17]. Designers will need to understand the limitations of 3D printing systems and take them into account in their designs, as not all designs are 'printable' [15]. Moreover, C3DP requires early design using a digital model in order to be able to integrate subsequent manufacturing and assembly processes into the 3D printing planning process [18]. As a result, the design and manufacturing processes are much more closely linked than in the conventional planning and construction process. This has been demonstrated by the production of the first 3D printed house in Beckum, Germany [18].

Creating a Printing Information Model (also known as a Fabrication Information Model) requires intensive collaboration between those involved in the project [16,19]. The Building Information Modelling (BIM) method plays an important role here. It enables the architect in the design process to plan in a way that is suitable for fabrication, in coordination with specialist engineers (see also section 3.2) [19,20]. With the help of a digital model, the effects of design changes are immediately visible to all those involved in the project. This makes it possible to create a high degree of planning reliability [18]. According to [15], however, it will no longer be possible to plan during the construction phase because the planning effort for 3D printing would increase. As a justification for this, it can be added that the planning would be subject to fundamental changes to an yet unkown extent and that individual phases of the planning would have to be repeated. In addition, early involvement of the various stakeholders is an important prerequisite for forward shifting design decisions to the early design process [12]. This requires a collaborative and integrated organisation of the team to improve construction project delivery [12].

3.2. (Early) Integration of construction expertise into the design stages

The design and planning process for printed structures (here: buildings) is similar to that for conventional buildings (masonry or reinforced concrete) [12,15,18]. Similarly, the (3D printing) design process starts with the owner working with the designer to define the owner and project objectives [15,18]. At present, the initial design process of conventional (cast-in-place) concrete structures does not pay much attention to a manufacturable and constructable design [15]. In current 3D printing pilot projects, the possibilities and limitations of the technology are usually explicitly considered from the outset, so that early integration of construction expertise and intensive collaboration are the result [8].

At present, the required expertise is generally made available by 3D printing companies, who can (and will continue to) complement the project and planning team (for example, as 3D printing experts; see 3.3) [8,20]. With C3DP technology, this form of intensive collaboration must take place in order to create a holistic design process in which the manufacturing and assembly steps of the construction process are considered at an early stage [21]. In order to be able to work outside the traditional design and construction paradigms, the project team should be made up of specialists in concrete technology, structural design, mechanical engineering and execution of construction tasks. This is particularly important given the experience of dealing with the still new 3D printing technology and the associated possibilities and limitations [15]. Design for (additive) manufacturing/3D printing principles will play an important role in future design and planning processes [15].

3.3. Changes in traditional roles and evolution of new roles

In the 3D design process, the architectural design and structural integrity of a 3D printed component or building structure need to be merged [9]. However, both Garcia de Soto et. al. (2019) and Spicek et. al. (2022) suggest that the traditional roles of architects and engineers will not be fundamentally changed by digital manufacturing technologies (such as C3DP) [12,15]. However, they predict that the early, intensive collaboration of architects, engineers, 3D printing specialists/builders will require coordination and therefore new roles might emerge as a consequence [12].

The introduction of digital manufacturing technology could lead to the emergence of so-called DFAB managers, coordinators and programmers, similar to the emergence of the roles of BIM managers and coordinators in the introduction of the BIM method [12,22].

While new design possibilities and new principles of cooperation will emerge for architectural design, but the core task is likely to remain the same, the workload will shift due to the envisioned (largely) automated construction in C3DP, especially in construction: from a high proportion of manual work towards a supervisory role [23,24]. There will be an increase in the management share for the machines and equipment (of the 3D printing system) and a decrease in the coordination/supervision share for skilled craftsmen [15]. Nevertheless, it is of course true that contractors will need to generate new knowledge and gain experience about the possiblities and limitations of C3DP as well [15].

C3DP will also enable clients to get closer to the digital design and planning process and have more influence on a customised building design [9,22]. It is commonly proclaimed that digitising manufacturing will lead to shorter project durations. However, Garcia de Soto et. al. (2019) see the introduction of these digital manufacturing technologies initially as an increase in the complexity of collaboration between the new and traditional roles in the design and construction phase, and therefore not resulting in shorter project durations but rather more intensive and earlier collaboration [12].

3.4. Transformation of organisational structures

Given the specific characteristics of C3DP and the particularities of project delivery, organisational structures need to be re-evaluated and transformed [15,24]. In order to realise the full benefits of C3DP, the three previous sections can be interpreted as an indication of the need to transform organisational structures.

In order to realise the holistic design and planning process that is required and demanded for C3DP, an active and early involvement of the different stakeholders is necessary. Garcia de Soto et al. (2019) believe that it is necessary to first move away from the traditional fragmented organisational structures towards a project based structural approach [12]. Ghaffar et al. (2020) go even further when they call for this to happen: Such an integrated design and execution process requires long-term partnerships focused on the development and implementation of AM systems [13]. Garcia de Soto et al. (2019) also predict this "platform-based" approach as a long-term result of a transformation of organisational structures [12]. In this approach, clients should be able to manage the design and construction process via a so-called dfab platform, which would enable (online-supported) coordination of design and automated production. Whether and to which extent the conservative and fragmented construction industry will embrace these profound changes is an open question.

4. Conclusion

Concrete 3D Printing not only offers a new architectural freedom or the machine-based erection of buildings. It also requires transformation of the usually linear planning and construction process into digital fabrication processes of material-efficient components. However, despite numerous pilot buildings, C3DP is still a niche technology and its impact on project delivery in terms of project organisation, responsibilities or decision points has not been widely researched. The aim of the study was to question whether the technology readiness or the current organisational structures prevent a faster integration of C3DP in the near future. For this purpose, a literature review was carried out in order to record the previous findings on the implications of C3DP on project delivery.

The results show that the traditional planning and construction process will continue to be valid only to a certain extent. On the one hand, new roles and changes in responsibilities may emerge, and on the other hand, in comparison to the traditional project delivery, an early contractor/competence involvement might be required in order to fully exploit the potential of C3DP. Therefore, for C3DP to become more integrated in the future, adopting alternative and more cooperative project delivery models should be applied.

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